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Feasibility of Fueling PWRs with Fuel Discharged from Breed and Burn Reactors

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Abstract

The fuel discharged from Breed and Burn (B&B) reactors contains a relatively high content of fissile plutonium (~10%). This study assesses the feasibility of reducing this fissile content while increasing the fuel utilization by loading the B&B discharged fuel, after reconditioning, into Pressurized Water Reactors (PWR). Two processes are examined for recycling the B&B reactor discharged fuel: the melt–refining process and the AIROX process. Both use processes that can remove a fraction of the fission products and cannot be used for actinide separation. It is found possible to load full PWR core with the reconditioned fuel and operate it to an additional burnup of up to 70,000 MWd/MT_{IHM} (AIROX processed fuel) and 105,000 MWd/MT_{IHM} (melt-refining treated fuel), while maintaining a negative coolant temperature reactivity coefficient . The burnup reactivity swing is significantly smaller than in conventional PWR cores. The B&B reactor fuel is highly proliferation resistant after being discharged from the PWR.

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Keywords: breed and burn; TWR; discharged fuel; recycling; AIROX; melt-refining; PWR

1. Introduction

Breed and Burn (B&B) reactors are fast reactors that, once initial criticality is established, can sustain criticality "indefinitely" when fueled with depleted uranium while operating in a once-through fuel cycle. In a B&B mode of operation depleted uranium is first converted into plutonium part of which is fissioned in situ. TerraPower has

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studied several designs of Breed and Burn reactors, which are also referred to as Travelling Wave Reactors (TWR) [1,2].

Previous studies [3,4] quantified the value of the minimum burnup that is required for sustaining the breed-and-burn mode of operation and the sensitivity of the minimum burnup to a number of design variables, such as fuel type, fuel volume fraction and neutron leakage probability. The practical minimum required average discharge burnup using metallic fuel and low leakage core was found [4] to be in the vicinity of 18%-20% FIMA (Fissions per Initial Metal Atom). At this burnup the discharged fuel contains a significant amount of fissile plutonium (~10%) which poses a proliferation risk. The high concentration of fissile plutonium also suggests that the discharged fuel can be farther utilized for energy generation. The objective of this study is to assess the feasibility of recycling the B&B discharged fuel into PWRs with the objectives of increasing the fuel utilization while reducing the fissile fuel content and, thereby, improving the discharged fuel proliferation resistance.

In order to maintain the proliferation resistance of the B&B fuel cycle, only fuel recycling processes that cannot partition actinides and separate actinides from most fission products are considered. Two processes that meet these requirements were examined – an AIROX-like process and the melt-refining process. The AIROX process has been developed and successfully demonstrated for oxide fuels [5,6] and it is assumed that the B&B discharged metallic fuel will be first converted into oxide form. The melt-refining process was developed in the EBR-II project for metallic fuel [7] and it is assumed that the melt-refined reconditioned fuel will be converted to oxide form. For this preliminary feasibility study both fuel reconditioning processes examined are assumed to be ideal, that is, loss-free.

The simplified study methodology is described in Section 2. Results of the attainable PWR moderator-to-fuel volume ratios along with the attainable burnup are summarized in Section 3. Section 3.5 discusses the effect of the additional irradiation in PWR on the discharged fuel characteristics.

2. Simplified Study Methodology

2.1. Density of oxide fuel

It is assumed that the B&B fuel is discharged at an average burnup of 18% FIMA and, after 1000 days of cooling, has the composition given in Table 1. This composition pertains to the fuel discharged from one of the TWR core designs [8]. The fuel to be loaded into the PWR contains most of the actinides, the Zirconium used in the metallic alloy (5 wt %) and the fission products (FPs) left after either the AIROX or the melt-refining processing. The Zr and FPs reduce the Heavy Metal (HM) density in the oxide fuel. Table 2 reports the removal fractions of elements from the B&B reactor discharged fuel that underwent either the AIROX or the melt-refining process.

The reprocessed oxide fuel density is estimated as follows:

$$\rho_{mixture} = \frac{1}{\frac{w_1}{\rho_1}+\frac{w_2}{\rho_2}+\cdots+\frac{w_i}{\rho_i}} \quad (1)$$

in which the ρ_i terms in the denominator are the densities of the oxides of the constituents of the fuel mixture while w_i are their weight %. Only one oxide form was assumed for each element. Some elements do not form oxides. For elements with unknown oxides, the pure element density was used.

The resulting density of B&B reactor fuel that underwent fuel processing 1000 days after discharge is calculated to be 9.95 g/cm^3 for the melt-refining process and 9.7 g/cm^3 for the AIROX process. Both resulting densities are smaller than the density of pure UO_2 that is 10.97 g/cm^3. The inferior density of the AIROX fuel is due to the higher content of fission products left over in the fuel. Table 3 compares the HM density in the various fuels.

2.2. PWR core modeling

The PWR core is represented, for this very preliminary feasibility study, by a single fuel pin unit cell in a square lattice. Reflective conditions are applied to all the outside boundaries of the unit cell. The unit cell moderator-to-fuel volume ratio is 1.66, the pitch is 12.6 mm and the outer fuel rod diameter is 9.5 mm. The Zircaloy clad is assumed to be 0.571 mm thick, while the gap is 0.082 mm thick, as used in [9]. The water density is 0.7 g/cm^3. A power density

of 322 W/cm^3 of fuel volume is assumed for the depletion analysis of the unit cell. This corresponds to a typical PWR core average linear heat generation rate of 176.5 W/cm [9]. The MOCUP code system [10] is used for the coupled neutronics and depletion calculations, performed with MCNP 1.51 [11] and ORIGEN 2.2 [12], respectively.

Table 1. Composition of B&B Reactor Discharged Fuel [8].

Nuclide	Mass fraction	Nuclide	Mass fraction	Nuclide	Mass fraction
^{238}U	8.74E-01	^{242}Pu	2.93E-04	^{245}Cm	4.62E-07
^{236}Np	1.26E-20	^{241}Am	1.41E-03	^{246}Cm	2.16E-08
^{237}Np	7.85E-04	^{242m}Am	1.29E-20	^{247}Cm	4.43E-10
^{238}Pu	4.40E-04	^{242}Am	1.29E-20	^{248}Cm	1.32E-20
^{239}Pu	9.95E-02	^{243}Am	2.44E-05		
^{240}Pu	2.16E-02	^{243}Cm	4.34E-07	Pu/HM	12.28%
^{241}Pu	9.55E-04	^{244}Cm	2.66E-06	Fis. Pu/Tot. Pu	81.81%

Table 2. Element Removal Fractions in Recycling Processes Examined.

	AIROX	**melt-refining**
Th	0%	95%
Am	0%	95%
other HM	0%	0%
FPs	100% T,C,Kr,Xe, I	100% Br,Kr,Rb,Cd,I,Cs
	90% Cs,Ru	95% Sr,Y,Te,Ba, La-Lu
	75% Te,Cd	
gas FPs	100% H,He,N,O,F,Ne,Cl,Ar,Kr,Xe,Rn	

Table 3. Heavy Metals Density for fuel types examined.

type of fuel	HM mass fraction	fuel density (g/cm^3)	HM density (g/cm^3)
UO_2	88.1%	10.97	9.65
melt refined B&B	75.8%	9.95	7.54
AIROX processed B&B	72.6%	9.70	7.04

The maximum discharge burnup the B&B reactor recycled fuel could undergo in the PWR core is estimated from the unit cell k_∞ evolution with burnup assuming n fuel batches and a 2.5% neutron leakage probability from the PWR core [13]. The core average reactivity is estimated from [13]:

$$\rho_{core} = \frac{f_1\rho_{\infty,1}+f_2\rho_{\infty,2}+\ldots+f_n\rho_{\infty,n}}{n} - 0.025 \quad (2)$$

where $\rho_{\infty,i} = \frac{k_{\infty,i}-1}{k_{\infty,i}}$ is the reactivity calculated from the unit cell for batch i and f_i is the fraction of the total core power generated by batch i. The value of f_i can be determined from a 3-D analysis of a representative core; for this preliminary analysis it is assumed to be $1/n$.

For a 5-batch core that operates with a Fuel-Cycle-Length FCL, the Beginning-Of-Cycle (BOC) reactivity and End-Of-Cycle (EOC) reactivities are:

$$\rho_{BOC} = \frac{\rho_0+\rho_{FCL}+\rho_{2*FCL}+\rho_{3*FCL}+\rho_{4*FCL}}{5} - 0.025 \quad (3)$$

$$\rho_{EOC} = \frac{\rho_{FCL}+\rho_{2*FCL}+\rho_{3*FCL}+\rho_{4*FCL}+\rho_{5*FCL}}{5} - 0.025 \quad (4)$$

where ρ_0 is the reactivity at time zero (fresh fuel), ρ_{FCL} is the reactivity after the fuel has resided in the core one cycle, ρ_{2*FCL} is the reactivity of the fuel that resided in the core two cycles and so on. The cores of interest are the

ones for which both ρ_{BOC} and ρ_{EOC} are >1 for the highest possible discharge burnup. In this study we limit the analysis to five batch cores, so as to get an upper practical estimation of the attainable burnup. Larger number of batches could result in unrealistically short cycle length.

3. Results

3.1. Reference Moderator to Fuel Volume Ratio

Results of k_∞ evolution with burnup are shown in Figure 1 for a moderator-to-fuel volume ratio of 1.66 (indicated as 1.7 in the rest of this study) – corresponding to the reference PWR. Results are calculated for UO_2 fuel enriched to 4.5%, for melt-refined B&B reactor fuel and for AIROX treated B&B reactor fuel. It is observed that the melt-refined fuel k_∞ evolution is nearly linear, significantly flatter than that of the UO_2 fuel and crosses the k=1 axis at approximately the same burnup – 38,000 MWd/MT_{IHM}; it is therefore expected that the two fuels will have similar discharge burnup. It is also expected that the melt-refined B&B reconditioned fueled PWR core will have significantly smaller burnup reactivity swing to compensate. The flatter k_∞ evolution is a result of the following factors: the high fissile nuclide content combined with large concentration of fission products and hard neutron spectrum relative to the reference PWR. The relative change in the fissile content per unit burnup is smaller in the melt-refined B&B discharged fuel than in the enriched uranium fuel and certain fission products loaded with the B&B fuel function as burnable poison. It is also noted that this fuel does not have an initial sharp decrease in k_∞ as in enriched UO_2 fueled core. This is due to the significantly smaller reactivity effect of ^{135}Xe in the PWR core loaded with B&B reactor fuel due to its very high initial fissile fuel and FP concentrations, the hard neutron spectrum, as well as to the initial rapid decline in the concentration of certain high cross-section fission products such as ^{149}Sm and ^{157}Gd. Figure 2 shows the spectrum of PWR, melt-refined and AIROX-treated fuel at Beginning of LIFE and at 55,000 MWd/MT_{IHM}. The three pronounced depressions in the spectra are due to the strong absorbing resonances of ^{239}Pu and ^{241}Pu at ~0.3 eV, of ^{240}Pu at ~1 eV and of ^{238}U at ~ 6.67eV. Figure 3 shows absorption rate of selected FPs in PWR; it is evident that some FP such as ^{149}Sm and ^{157}Gd act as burnable poisons.

For AIROX treated fuel it is observed that criticality cannot be established at any burnup. To more thoroughly evaluate the feasibility of using the B&B reactor reconditioned fuel in PWR, the moderator-to-fuel volume ratio is varied and the attainable discharge burnup and resulting coolant reactivity coefficient are quantified.

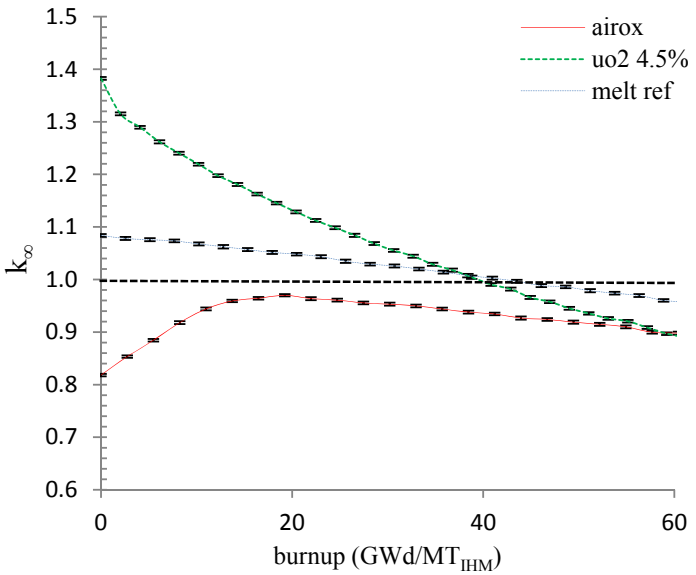

Figure 1. k_∞ evolutions in the reference PWR unit cell for 18% FIMA B&B reactor fuel reconditioned using an AIROX-like or a melt-refining process and for standard UO_2 fuel with 4.5% ^{235}U enrichment. Error bars indicate the 95% confidence interval for MCNP5 k calculations.

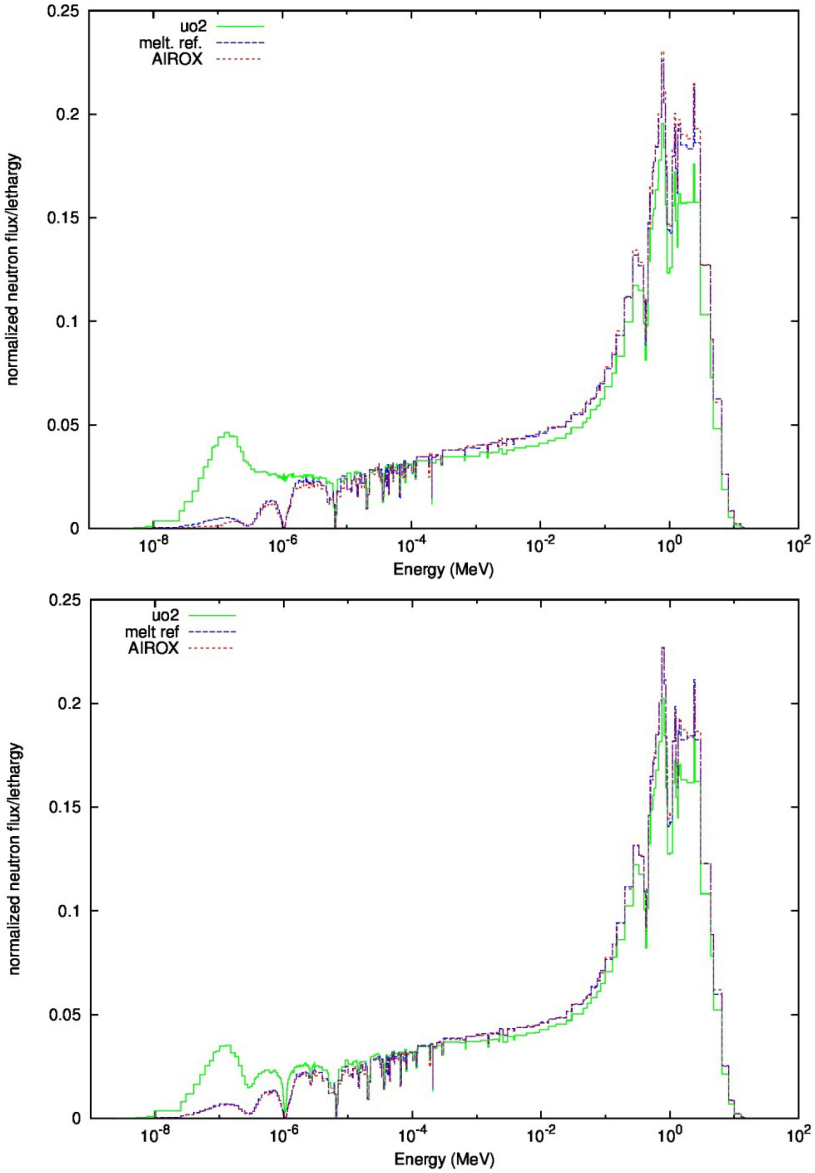

Figure 2. Neutron spectra in reference PWR unit cell for 18% FIMA B&B reactor fuel reconditioned using an AIROX-like or a melt-refining process, for standard UO_2 fuel with 4.5% ^{235}U enrichment at Beginning of Life (BOL) (*top*) and at 55,000 MWd/MT_{IHM} (*bottom*).

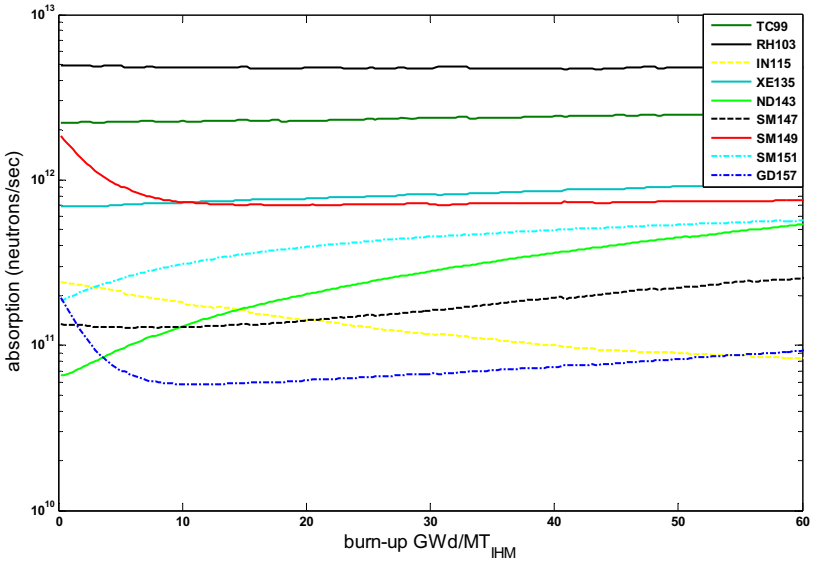

Figure 3. Absorption rate in selected fission products in PWR loaded with18% FIMA B&B reactor fuel reconditioned using a melt-refining process for a unit cell of 10 cm height.

3.2. Melt-refined fuel performance versus moderator to fuel volume ratios

Evolution of k_∞ for moderator-to-fuel volume ratio M/F=1.7, 2.8, 4.1, 5, 6.2, 9.9 are shown in Figure 4. The

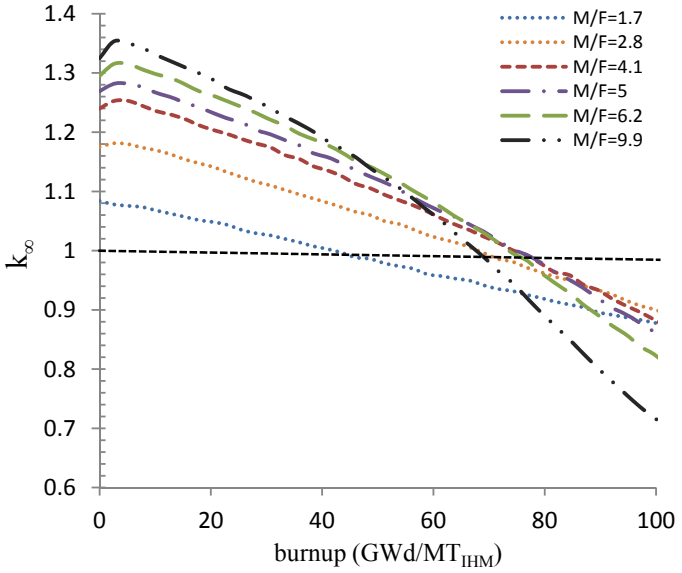

Figure 4. k_∞ evolutions in the reference PWR unit cell for 18% FIMA B&B fuel reconditioned using a melt-refining process for various PWR moderator-to-fuel volume ratios.

moderator-to-fuel ratio is varied in this study by increasing the cell pitch. It is possible to increase the M/F ratio also by diluting the fuel with a low-absorbing material (an "inert matrix") while maintaining the nominal P/D. The latter approach is expected to have a tolerable reactivity penalty. The initial value of k_∞ as well as its rate of change with burnup increases with M/F. The initial increase in reactivity becomes more pronounced for higher M/F cores; it is due to the softer spectrum that increases the rate of neutron capture in strongly absorbing fission products loaded with the reconditioned B&B discharged fuel. Using a polynomial fit to each of the curves of Figure 4, the 5-batch EOC core average k_{core} was calculated as a function of the cycle length using Equation (4). Figure 5 reports the results obtained while Table 4 summarizes the maximum attainable discharge burnup. It is observed that the burnup attainable in the reference M/F ratio of 1.7 of 49 GWd/MT_{IHM} is close to that being achieved in todays' PWR using enriched uranium (~55 GWd/MT_{IHM}). However, by increasing the moderator-to-fuel volume ratio the attainable burnup can be doubled. The reduction in the attainable burnup for M/F > 4.1 indicates overmoderation.

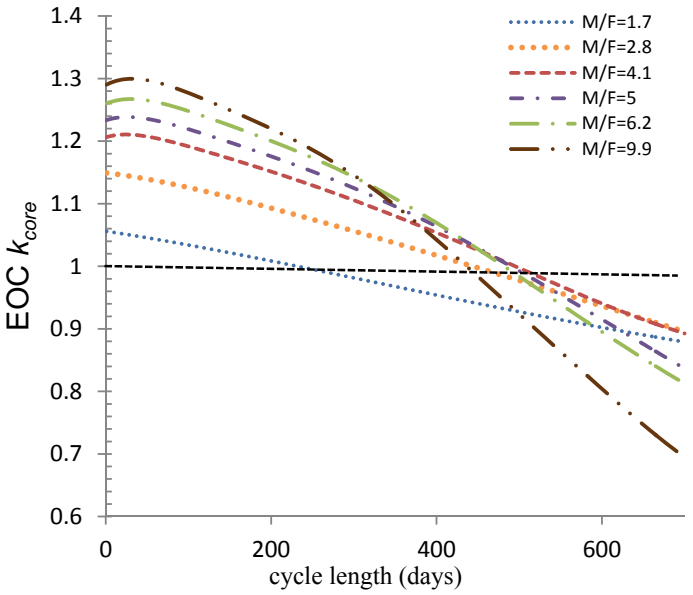

Figure 5. End-Of-Cycle k_{core} in the reference PWR for 18% FIMA B&B fuel reconditioned using a melt-refining process for various moderator-to-fuel volume ratios as a function of the cycle length.

Table 4. Maximum Discharge Burnup for Melt-refined Fuel and AIROX fuel for Various Moderator-to-Fuel Volume Ratios.

M/F	P/D	discharge burnup MWd/MT_{IHM}	Cycle length (days)
1.7	1.33	49,485	232
2.8	1.57	94,704	444
4.1	1.79	105,583	495
5.0	1.92	104,516	490
6.2	2.11	102,596	481
9.9	2.56	92,998	436

3.3. AIROX-treated fuel performance versus moderator to fuel volume ratio

Figure 6 shows the k_∞ evolution when using AIROX treated fuel for several moderator-to-fuel volume ratios. These k_∞ evolutions are of a parabolic shape; the relatively large initial increase in reactivity is due to the larger

concentration of fission products in the AIROX processed fuel than in the melt-refined fuel. It is observed that in all the M/F ratios examined above the reference value, k_∞ exceeds unity at a certain burnup range. This implies that for large enough M/F values a multi-batch core can be designed to have fuel batches with sufficient excess reactivity to compensate for the reactivity deficiency of the fresh fuel batch. However, in order to establish initial criticality using the AIROX treated B&B discharged fuel it will be necessary to add fissile fuel in the amount capable of generating sufficient number of excess neutrons to incinerate that amount of poisonous fission products that will bring the AIROX treated fuel k_∞ above 1.0.

Figure 7 shows the core average k for selected M/F ratios as a function of the cycle length for both BOC and EOC in a 5-batch core. These results were obtained by applying Equations (4) and (5) using polynomial fits to the curves of Figure 6. The maximum attainable burnup can be graphically deduced from Figure 7 as the highest burnup for which both EOC and BOC k_{core} are >1. It is observed that for M/F = 2.8 the BOC k_{core} is always <1 implying that a critical reactor cannot be achieved for this M/F value. The vertical line in Figure 7 marks the longest cycle length for which the M/F = 5 core can be critical at BOC. Table 5 summarizes the maximum attainable cycle length and burnup for selected M/F ratios. It is concluded that even with AIROX reconditioning the additional burnup the B&B reactor used fuel can accumulate in an increased moderation PWR core exceeds the ~55 GWd/tHM of contemporary enriched uranium fueled PWRs. This burnup is, however, smaller that attainable using the melt-refining process.

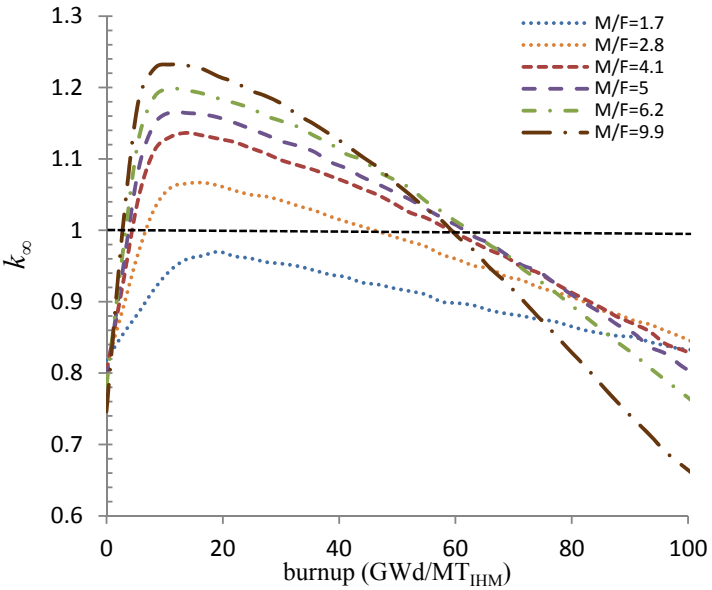

Figure 6. k_∞ evolution in the reference PWR unit cell for 18% FIMA B&B fuel reconditioned using an AIROX-like process for various moderator-to-fuel ratios.

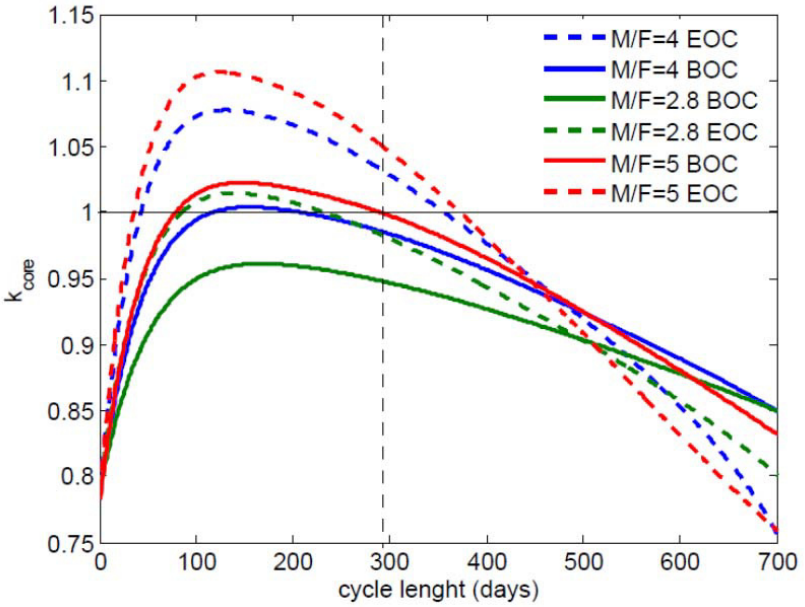

Figure 7. k_{core} at BOC (solid line) and EOC (dashed line) as a function of cycle length in the reference PWR unit cell for 18% FIMA B&B fuel reconditioned using an AIROX-like process for various moderator-to-fuel ratios. The vertical line indicates the maximum cycle length for M/F=5.

Table 5. Maximum Discharge Burnup for AIROX treated fuel for Various Moderator-to-Fuel Volume Ratios.

M/F	P/D	discharge burnup MWd/MT$_{IHM}$	Cycle length (days)
1.7	1.33	-	-
2.8	1.57	-	-
4.1	1.79	47,380	207
5.0	1.92	66,149	289
6.2	2.11	76,220	333

3.4. Reactivity coefficients

To ensure safety, the PWR cores fed with discharged B&B fuel must have negative temperature coefficients of reactivity over the entire cycle. Of most concern is the coolant temperature reactivity coefficient; it is the focus of this section. As PWRs use soluble boron for excess reactivity control, the effect of soluble boron on the coolant temperature reactivity coefficients is accounted for. For melt-refined fuel, the maximum excess reactivity and, hence, maximum boron concentration, are at the beginning of cycle. However, with AIROX treated fuel the core excess reactivity peaks at the central part of the cycle. Figure 8 shows the k_{core} variation over a cycle calculated using Equation (2). The highest reactivity points are identified for each M/F examined. The coolant temperature reactivity coefficient of the melt-refining case is also calculated at the EOC, when there is no boron, but the fuel composition is significantly different compared to BOC.

The coolant temperature reactivity coefficient at a given time in the cycle is deduced by simulating a unit cell the fuel composition of which is an average of the fuel composition in each of the five batches at the same time in the cycle. Natural boron is added to the water at the amount required to compensate for the maximum excess reactivity - between 1100 ppm to 2527 ppm. The water density is varied over a range of 50 degrees from 0.68 g/cm^3 (325 °C) to 0.76 g/cm^3 (277 °C) considering 15 MPa pressure. Figure 9 shows the reactivity coefficients inferred from these

calculations. It is concluded that the permissible PWR design space for AIROX treated TWR fuel is ~4<M/F<5.4, while for melt-refined fuel it is 1.7<M/F<4.5; the upper bound is estimated by extrapolation of Figure 9 results. The corresponding maximum attainable burnups are about 70 GWd/MT_{IHM} for AIROX and 105 GWd/MT_{IHM} for melt-refined fuel. Both burnups are higher than the ~55 GWd/MTU of typical enriched uranium fuelled PWR.

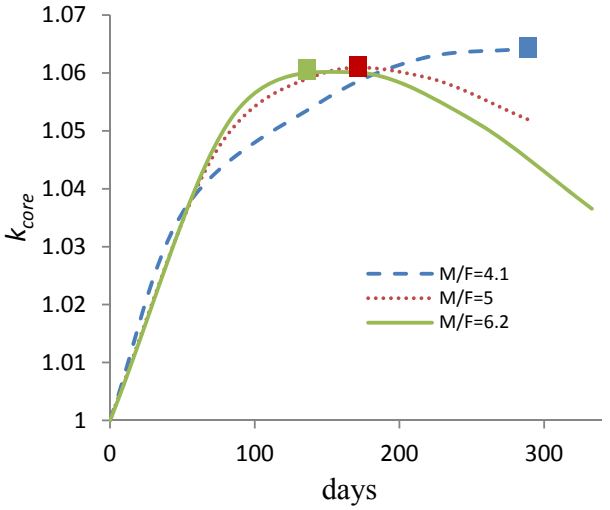

Figure 8. k_{core} evolution over a cycle for AIROX fuelled PWR for various M/F ratios. The highest reactivity points are identified with squares.

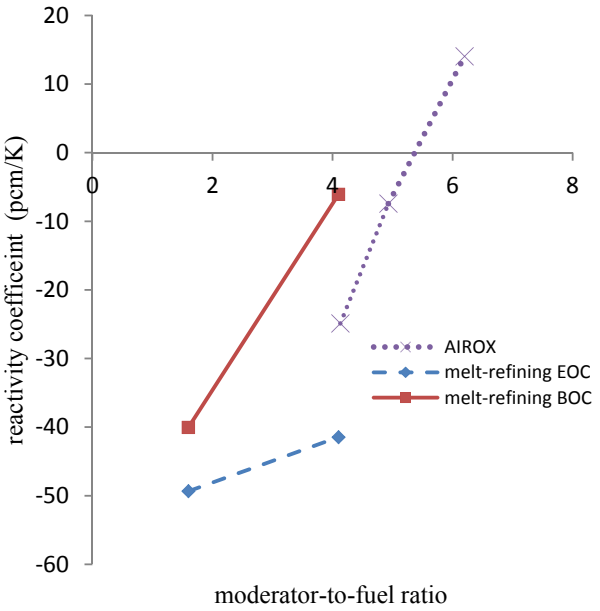

Figure 9. Coolant temperature reactivity coefficient for AIROX and melt-refining fuelled PWR cores for various M/F ratios.

3.5. Discharged fuel characteristics

Table 6 compares selected characteristics of the fuel discharged from PWRs for different feed fuel compositions and several M/F ratios. It is observed that the fissile Pu to total Pu ratio can decrease via additional irradiation in PWRs from 81% in the fuel discharged from the B&B core down to 38% for melt-refined fuel or 52% for AIROX treated fuel. Both values are smaller than the 68% of enriched uranium fueled PWR. The same applies to the total amount of plutonium discharged per unit of electricity generated by the fuel in the B&B reactor and PWR cores – 209 and 248 versus 281 kg/GWe-Y. Likewise for the total TRU discharged per unit of electricity generated.

Table 6 compares the Figure Of Merit (FOM) for proliferation resistance [14]:

$$FOM = 1 - log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{log_{10}2}}\right) \quad (5)$$

where M is the bare critical mass in kg, h is the heat content in W/kg, and D is the dose rate of $0.2 \cdot M$ evaluated at 1 m from the surface in rad/h. The more negative the FOM is, the higher is the proliferation resistance of the fuel. It is observed that for all the studied M/F ratios, except for the melt-refining M/F = 1.7 case, the FOM is negative; for certain designs even more negative than of the reference PWR. The additional irradiation step is therefore highly effective in making the final discharged fuel proliferation resistant.

Table 6. Characteristics of Discharged Fuel.

	B&B	**4.5% PWR**	**melt-refining**			**AIROX**	
			M/F=1.7	**M/F=2.8**	**M/F=4.1**	**M/F=4.1**	**M/F=5**
burnup (GWd/MTHM)	171.0	55.0	49.5	94.8	105.6	47.4	66.1
Pu/HM	12.28%	1.54%	10.73%	7.27%	5.46%	9.45%	7.77%
Fiss. Pu/Tot.Pu	81.81%	67.93%	72.43%	52.87%	38.16%	64.45%	52.26%
Kg of Pu/GWeY	597	281	360	209	148	309	248
Kg of TRU/GWeY	608	312	369	221	161	317	258
FOM	0.90	-0.38	0.09	-0.57	-0.76	-0.29	-0.49

Breed-and-burn reactors have additional important proliferation resistant attributes including lack of need for uranium enrichment and for partitioning of plutonium except for the initial fuel loading.

4. Conclusions and Recommendations

Based on this preliminary study it is concluded that it is feasible to operate PWRs with B&B used fuel that underwent a proliferation-resistant reconditioning using either the melt-refining or AIROX-like process. The additional burnup the B&B reactor recycled fuel can achieve in the PWR is up to 70 GWd/MT_{IHM} for AIROX treated or 105 GWd/MT_{IHM} for ideal melt-refining treated fuel. The burnup reactivity swing is significantly smaller than of conventional PWR cores due to a combination of several phenomena: high initial concentration of fission products and fissile fuel, small relative reduction in the fissile fuel content with burnup, and depletion of certain fission products that function as burnable poisons. In order to achieve initial criticality of the PWR core that is loaded with AIROX treated B&B discharged fuel it will be necessary to add fissile fuel.

The fissile plutonium fraction discharged from the PWR fueled with B&B recycled fuel is smaller than in standard PWR used nuclear fuel, and so are the total amount of plutonium and of TRU per unit of electricity generated. The B&B fuel that underwent irradiation in PWR can be even more proliferation resistant than a standard PWR used nuclear fuel.

The approach used for increasing the moderator-to-fuel volume ratio in this preliminary feasibility study was to increase the pitch while retaining the standard PWR fuel rod diameter. Such an approach will result in a significant penalty on the attainable power density. An alternative approach recommended for investigation is to use a standard

rod diameter and M/F volume ratio but dilute the HM with a low absorbing material such as Zr or SiC. Such diluents are recently being considered even for enriched uranium based “inert matrix” fuel.

Acknowledgements

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